Shallow VSP for Near-Surface Structure and Statics*

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Abstract

Shallow vertical seismic profiling (VSP) data can serve as a near-surface characterization tool-providing velocity values for static corrections and reflection images for structure. Two hydrophone VSP surveys were acquired in shallow (~40 m), fluid-filled boreholes in the West Castle River area of southern Alberta. The processed hydrophone VSP data showed distinct first arrivals and credible reflections. The P-wave velocity model is obtained by travel time inversion. The velocities range from 910 m/s in the shallow sands to 3500 m/s in the deeper competent shales. Event identification in the field data is aided by synthetic seismograms generated using a finite-differencing algorithm. The synthetic seismograms were also used in developing and testing a processing flow for the field VSP data. A promising correlation between the VSPCDP map of the field and synthetic data indicates considerable potential for the VSP hydrophone technique in near-surface characterization.

Introduction

Vertical seismic profile (VSP) data can be used as a near-surface imaging tool directly or as an aid to the processing and interpretation of deeper seismic reflection data. In the shallow case, VSP information can be applied for geotechnical purposes (building and dam design) as well as ground water exploration. For deeper targets, accurate near-surface velocity information obtained from VSP data can be used for seismic survey design and static correction. The VSP data are typically acquired using tools containing three-component (3-C) geophones clamped to the borehole wall. Coupling the geophone to the borehole wall is important for recording the true earth motion, but the procedure can be complicated and time-consuming (Gulati et al., 2001). A less expensive and rapid VSP acquisition technique is to use a hydrophone string. Hydrophones are pressure-sensitive detectors that can be suspended in a fluid-filled borehole without clamping to the borehole; so they are relatively easy to deploy and a large number of them can be used simultaneously. Previous experiments that evaluated the effectiveness of vertical hydrophone arrays on a land survey were carried out by Marzetta et al. (1988), Krohn and Chen (1992), and Gulati et al. (2001). We conducted two hydrophone VSP surveys in southern Alberta to test the viability of this shallow VSP concept.

Surface Hydrophone VSP Data Acquisition

In August 2006, shallow hydrophone VSP data were collected from two wells (called the Lodge and Duplex wells) at the base of the Castle Mountain ski resort in southern Alberta; the well's depths are 43 m and 32 m, respectively (Figure 1a). The resort is located near the West Castle River of southern Alberta. This is a mountainous region that hosts recreation, ecological reserves, and hydrocarbon production. The seismic source for our surveys was a 7.4 kg sledge hammer striking a spiked aluminum cylinder set firmly on the surface at various offset distances (15 m offset shown here) away from the wellhead (Figure 1b). The detector was an eight-element hydrophone array placed below the water level and the receiver-increment in the survey was 0.25 to 1 m. The total acquisition time to deploy the array and record five VSP shot records was less than 3 hours. Recording was done with a Geometrics R60 seismograph using a high-cut filter of 500 Hz, a sampling interval of 0.5 ms, and trace lengths of 512 ms. Figure 2a shows the raw shot gather for a source offset 15 m from the Lodge Well.

Synthetic VSP Seismogram

The P-velocity model used for creating the synthetic seismogram is developed by tracing rays through a layered earth model and matching the observed first-arrival times (Wong et. al., 2006). The velocity model is refined until its estimated first-arrival time matches the observed first-arrival time with an error less than 1 ms. Depth and thickness of the velocity layers are assigned according to the lithologic description outlined in the water well drilling report.

The processing flow was revised and tested using the synthetic VSP seismograms. The synthetic seismograms are generated using a finite-differencing algorithm (Manning and Margrave 2002) that employs the acoustic wave equation (Figure 2b). The offset-receiver geometry and acquisition parameters are set to represent the field acquisition.

Processing the Hydrophone VSP Data

From the raw data (Figure 2a), dead traces were edited prior to processing. First break times were picked from the raw data. Due to shot strength variation and near surface geology changes, traces from raw field records may have wildly varying total root-mean-square power levels: Thus, each trace in the flattened raw data is equalized. The downgoing wavefields are separated from the pre-processed data using a 15-point-median velocity filter and these wavefields are subtracted from the pre-processed data to obtain up-going, any remains of downgoing waves and tube waves. The extracted up-going wavefields were deconvolved to suppress noise, multiple and tube waves. The selection of a good deconvolution operator window size is based on its ability to collapse the down-going energy into a single, band-limited spike. The deconvolution design window was 150 ms with an operator length of 20 ms and 1% pre-whitening. Using the designed deconvolution operator, the up-going and down-going wavefields were deconvolved. Normal moveout was corrected using the root-mean-square velocity derived from a velocity analysis and then followed by VSPCDP stacking with a bin size of 10 cm (Figure 3b).

Results and Interpretation

The synthetic data were processed according to above processing steps. Figure 3 compares the synthetic VSPCDP stack (Figure 3a) and the observed VSPCDP stack (Figure 3b) along with the velocity model converted into a two-way-travel (TWT) time. As shown in the highlighted box of Figure 3a, we see three seismic boundaries (at 28 ms, 43 ms, and 65 ms) that we associate with the three water-bearing gravel layers (Figure 1b). We also observe that multiples arising from these reflectors are suppressed after the deconvolution. The difference in depths of the reflectors may be a result of an inaccurate assignment of the velocity layer's thickness which was solely dependent on water well drilling report. Also errors in velocity estimation using ray-tracing method may have contributed to the displacement of the reflectors. The discontinuation of reflector toward the far-offset (> 3m) may be due to the remnant of down-going or tube waves interfering with the up-going wavefields.

Conclusion

Two shallow, multi-offset VSP data sets were acquired in the West Castle River area of southern Alberta. These hydrophone VSP data are rapidly and inexpensively collected. A P-wave velocity model, which is obtained by travel-time inversion, indicates velocities ranging from 910 m/s in the shallow sands to 3500 m/s in the deeper competent shales. A synthetic VSP seismogram, which is generated from a finite-differencing method, is used as a guide for interpreting the near-surface hydrophone VSP data. The two-way-travel times of the seismic reflectors in the VSPCDP stack of the observed VSP data agree reasonably well with positions of the seismic reflector as suggested by the velocity model; especially the tops of three water-bearing gravel layers (32 ms, 42 ms, and 65 ms in two-way-travel time) that are resolved by the VSPCDP stack. The velocity information and imaging quality of the hydrophone VSP data provide considerable promise for the technique's use in near-surface characterization (e.g., for ground water exploration) and statics determination for related seismic processing.

Acknowledgement

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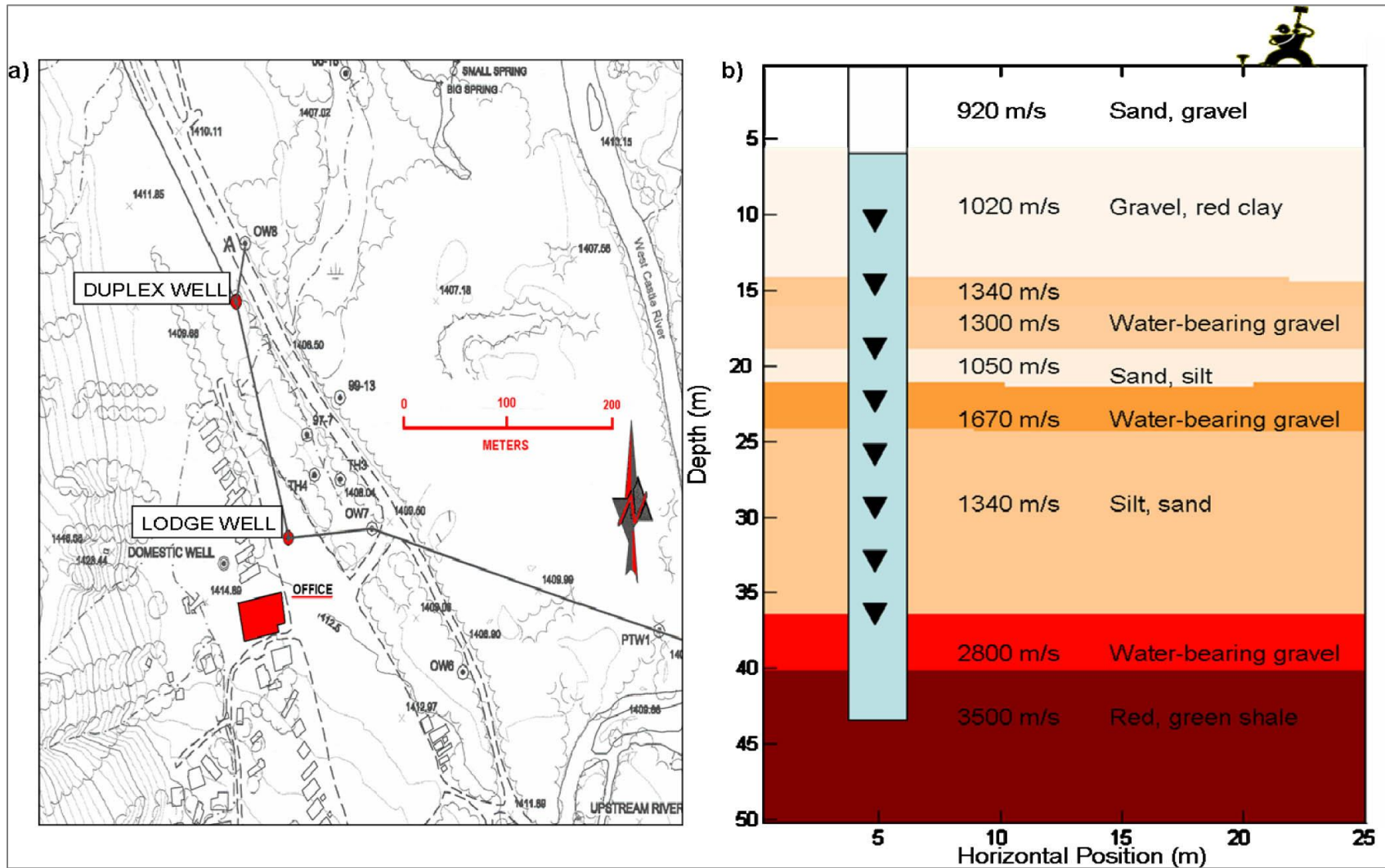
Figure 1. a) Location of wells (Lodge and Duplex wells) near the Castle Mountain Resort, in southern Alberta; b) 15 m source-offset with receivers positioned at depths of 10-43 m. The borehole is filled with water up to depth of 6.6 m. The lithology description is provided by a water-well drilling report.
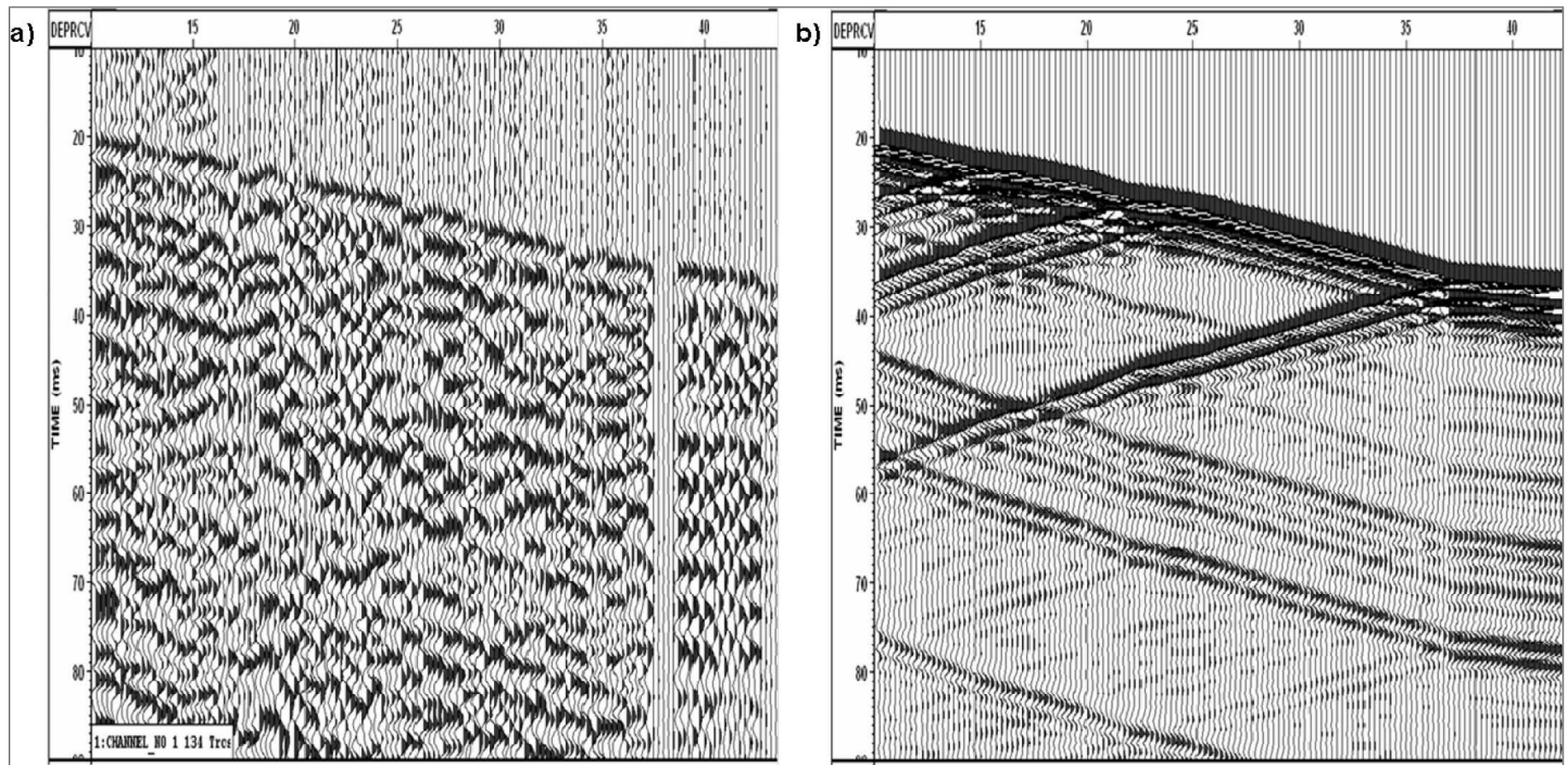
Figure 2. a) A shot gather of raw hydrophone VSP data from a 15 m source offset; b) A shot gather of synthetic VSP data using 15 m source offset.
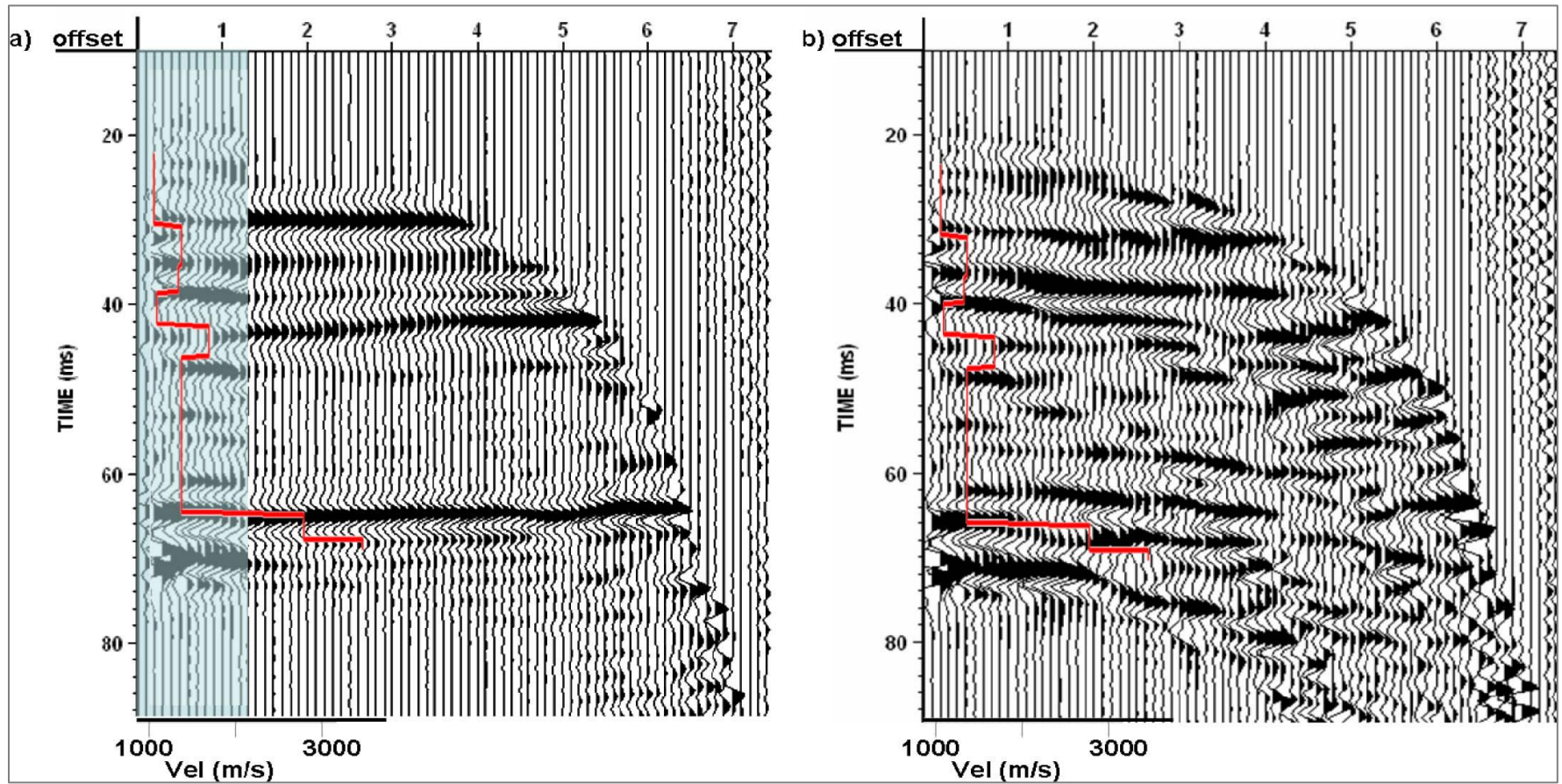
Figure 3. Normal moveout corrected and VSP-CDP stacked results of deconvolved: a) synthetic (the blue box highlights near-offst CDP map of the field data for its correlation with the synthetic CDP map) and b) field data.